

Top production asymmetry (A_{FB} , A_C) measurements at Tevatron and LHC

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Top A_{FB} @ Tevatron

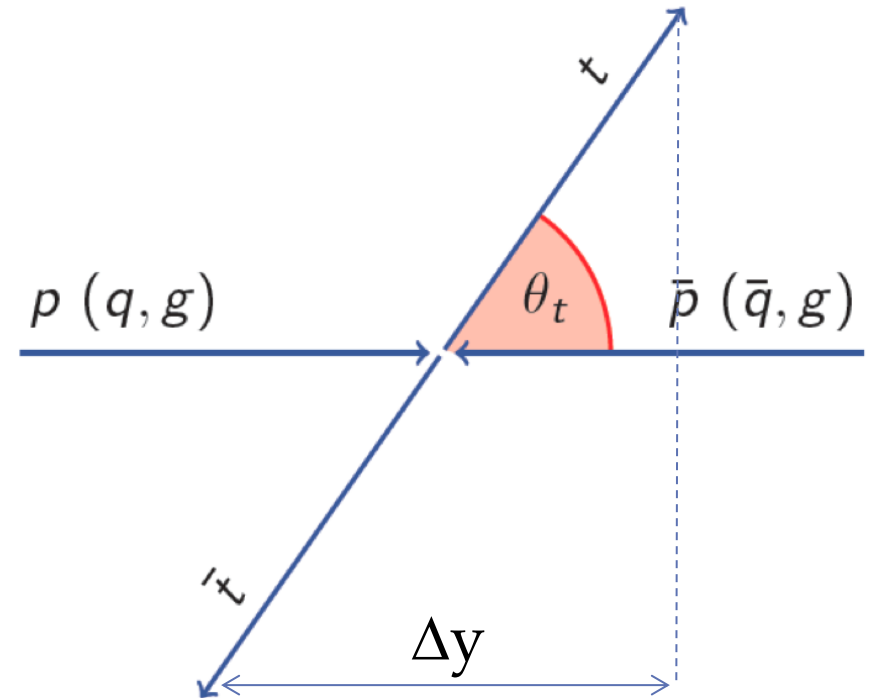
- ✓ CP-even initial state at the Tevatron proton-antiproton ($p\bar{p}$) collider
- ✓ Top A_{FB} reflects the asymmetry in the top quark production angle in the $t\bar{t}$ rest frame.
- ✓ Top direction is measured with frame-invariant difference of the top and anti-top quark rapidities, $\Delta y = y_t - y_{\bar{t}}$ where

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

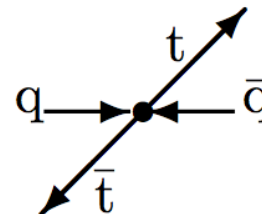
- ✓ FB Asymmetry is defined by

$$A_{FB} = \frac{N_{\Delta y > 0} - N_{\Delta y < 0}}{N_{\Delta y > 0} + N_{\Delta y < 0}}$$

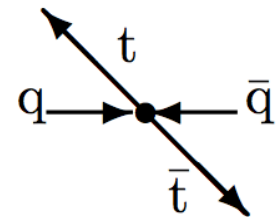
- ✓ Anomalous A_{FB} could be an indirect indication of new physics.



Forward

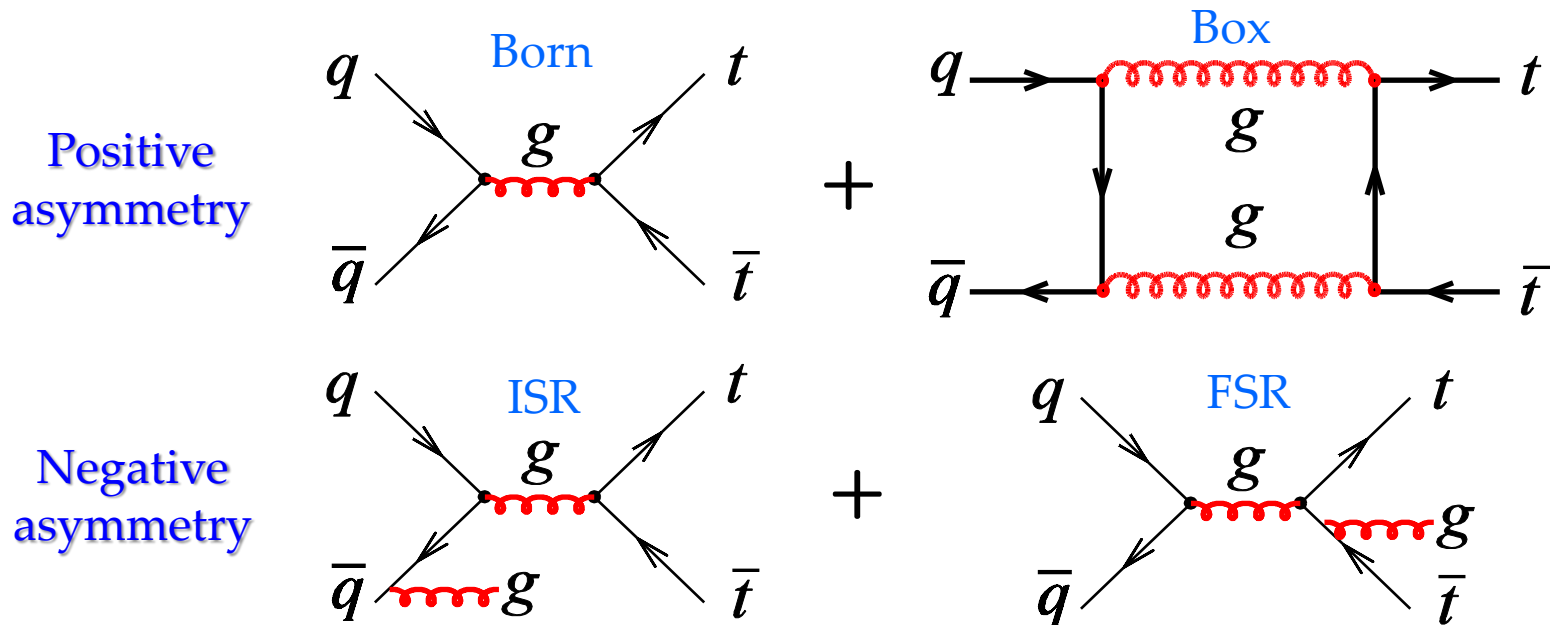


Backward



Top A_{FB} in Standard Model

- ✓ LO only : No forward-backward asymmetry
- ✓ Inclusive NLO prediction (QCD+EWK) : $A_{\text{FB}} = 8.8 \pm 0.6\%^*$
 - Terms of order α_s^3 in the partonic cross section $d\hat{\sigma}(q\bar{q} \rightarrow t\bar{t}X)$
 - Interference of the Born diagram with the 1-loop box and crossed box diagrams
 - Interference of initial and final state radiation

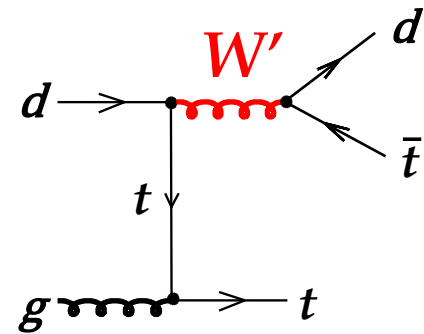
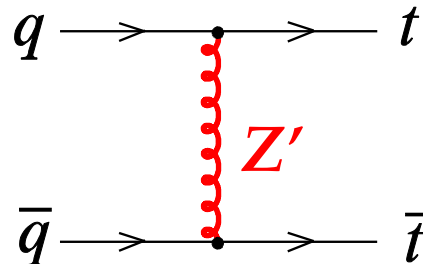
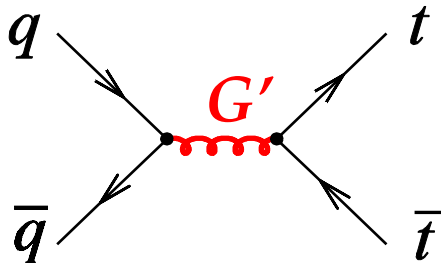


* W. Bernreuther and Z.-G. Si, Phys.Rev. D86, 034026 (2012)

Top A_{FB} in New Physics

✓ Presence of new physics could make asymmetry

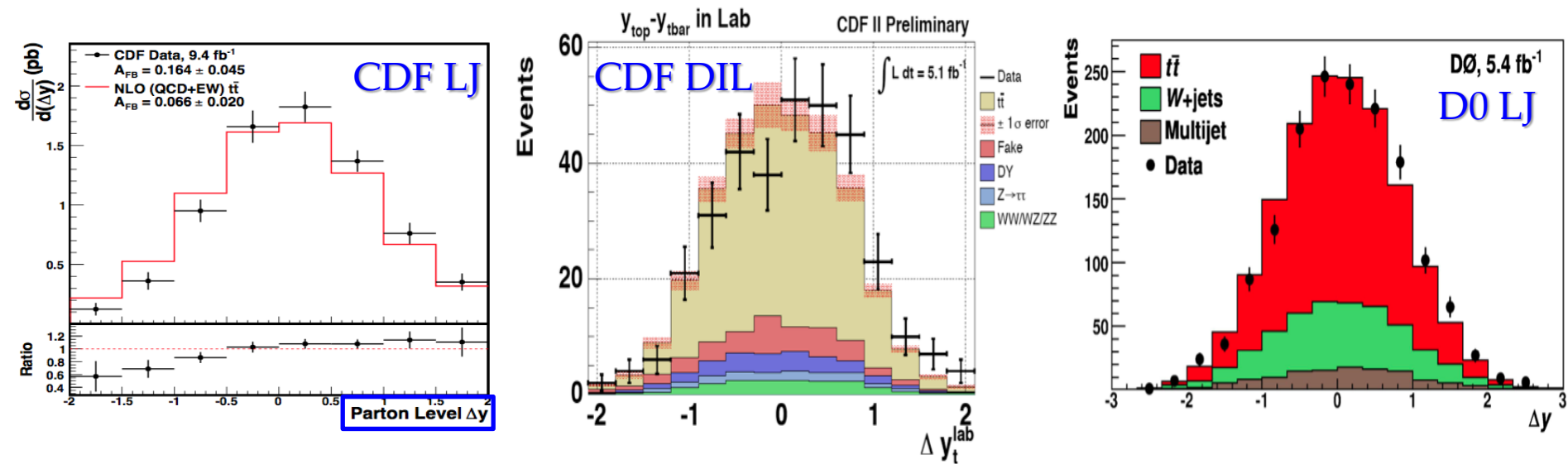
- Axial vector exotic gluon G' coupling
- Z' exchange
- W' interaction
- Etc...



✓ Things to have to explain by BSM

- Measured $t\bar{t}$ cross section (σ) and $d\sigma/dM_{t\bar{t}}$ are in good agreement with SM at Tevatron and LHC
- Tiny A_C at LHC and No other indications related to A_{FB}

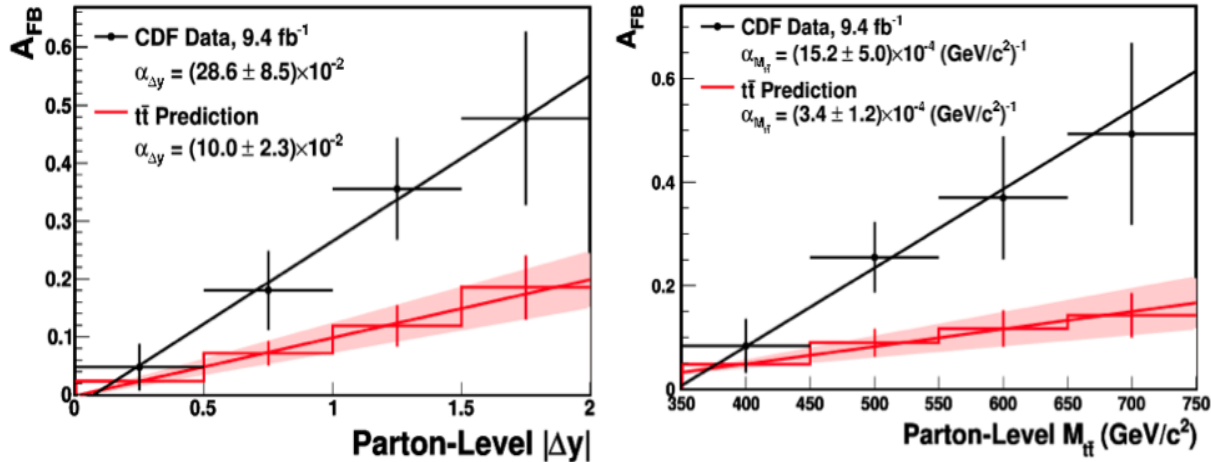
Top Δy asymmetry at Tevatron



- ✓ CDF l+jets(LJ) - 9.4 fb^{-1}
 - Observed $A_{FB} = 6.6 \pm 2.0\%$, **Parton-level $A_{FB} = 16.4 \pm 4.5\%$** [Just accepted for publication in PRD]
 - Many various checks (dependence on kinematic properties, Angular cross section and Leptonic A_{FB}) done with full CDF data set.
- ✓ CDF dilepton(DIL) - 5.1 fb^{-1}
 - Observed $A_{FB} = 13.8 \pm 5.4\%$, **Parton-level $A_{FB} = 41.7 \pm 15.7\%$**
 - Working on the updated results with full CDF data set
- ✓ D0 l+jets(LJ) - 5.4 fb^{-1}
 - Observed $A_{FB} = 9.2 \pm 3.7\%$, **Parton-level $A_{FB} = 19.6 \pm 6.5\%$** [PRD 84, 112005 (2011)]
 - Consistent with the CDF results. New results with full data set (9.7 fb^{-1}) will be updated soon.
- ✓ D0 dilepton(DIL) - 5.4 fb^{-1}
 - Leptonic A_{FB} result is published [PRD 87 011103(R) (2013)]

Mass and Rapidity dependence of Top A_{FB}

CDF LJ



- ✓ Asymmetry linearly increases as a function of parton-level $M_{t\bar{t}}$ and $|\Delta y|$
- ✓ Slopes are 3σ from zero and $\sim 2.3\sigma$ from SM prediction

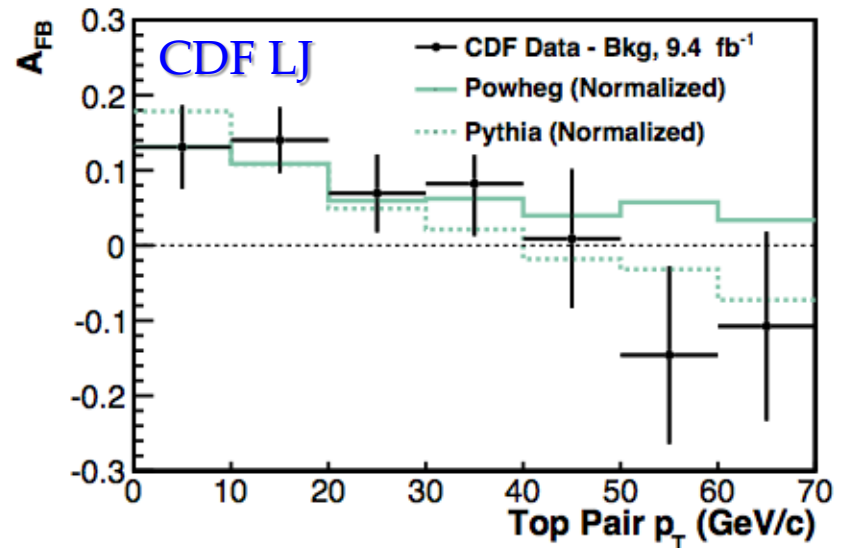
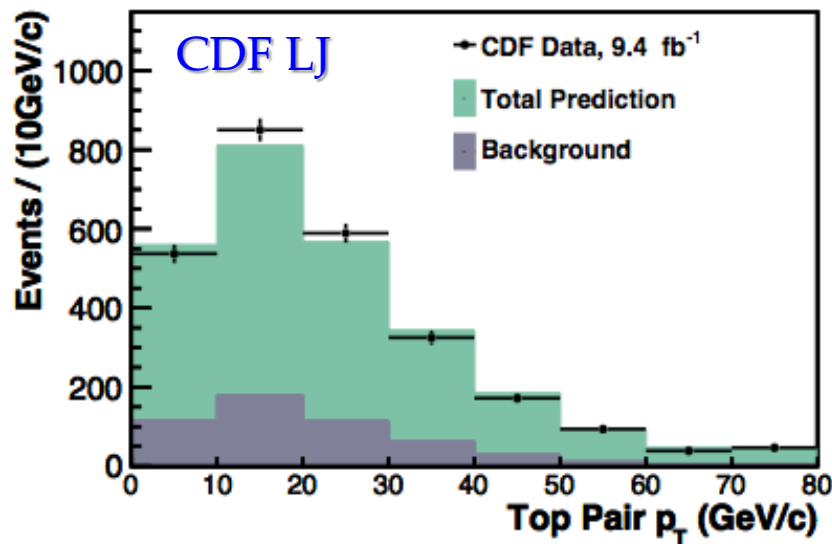
D0 LJ

TABLE III. Reconstruction-level A_{FB} by subsample.

| Subsample | A_{FB} (%) | |
|----------------------------------|----------------|---------------|
| | Data | MC@NLO |
| $m_{t\bar{t}} < 450 \text{ GeV}$ | 7.8 ± 4.8 | 1.3 ± 0.6 |
| $m_{t\bar{t}} > 450 \text{ GeV}$ | 11.5 ± 6.0 | 4.3 ± 1.3 |
| $ \Delta y < 1.0$ | 6.1 ± 4.1 | 1.4 ± 0.6 |
| $ \Delta y > 1.0$ | 21.3 ± 9.7 | 6.3 ± 1.6 |

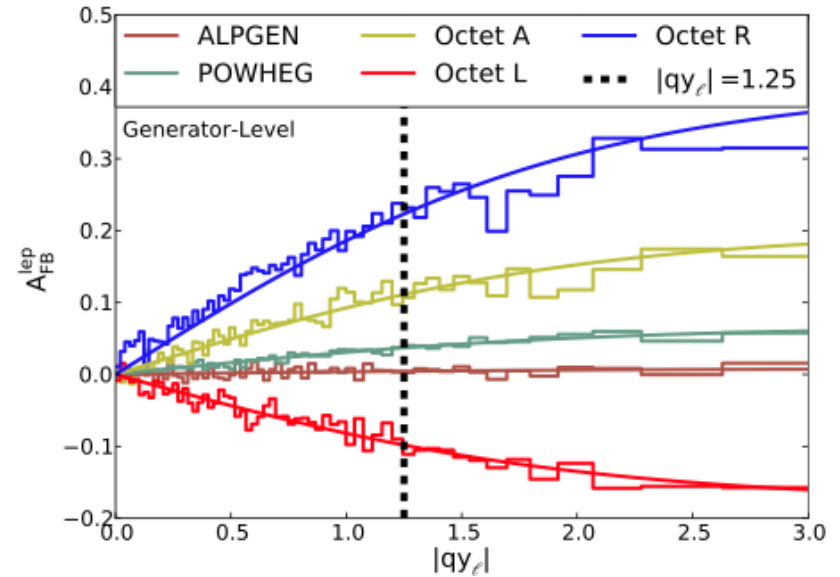
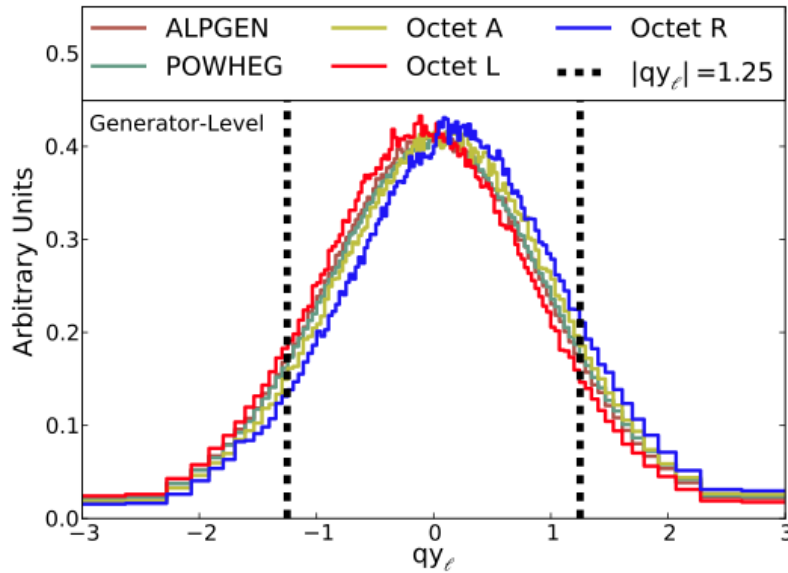
- ✓ Larger A_{FB} for high different rapidities, while A_{FB} vs. Mass slowly goes up (but not Parton-Level)

$p_T(t\bar{t})$ dependence of Top A_{FB}



- ✓ NLO (QCD+EW) $t\bar{t}$ + Background prediction agrees with data in top pair p_T distribution
- ✓ A_{FB} in the background subtracted data depends on the $t\bar{t}$ p_T spectrum
- ✓ The normalized shapes from Powheg(NLO) and Pythia(LO) describes well data, but the total asymmetry are not
- ✓ Reconstruction and modeling of the $p_T(t\bar{t})$ dependence of the asymmetry is robust, and that the excess asymmetry in the data is consistent with being independent of $p_T(t\bar{t})$

Lepton Asymmetry in $t\bar{t}$ Production

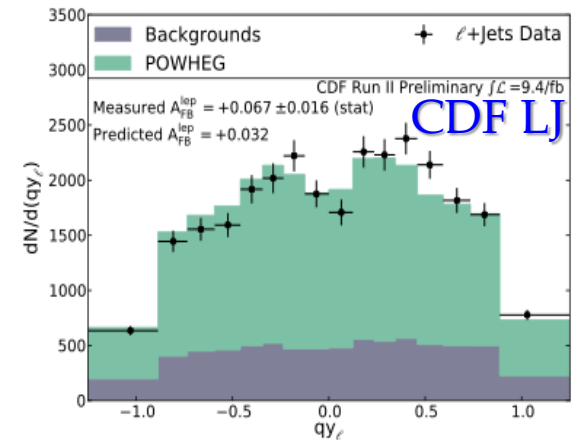
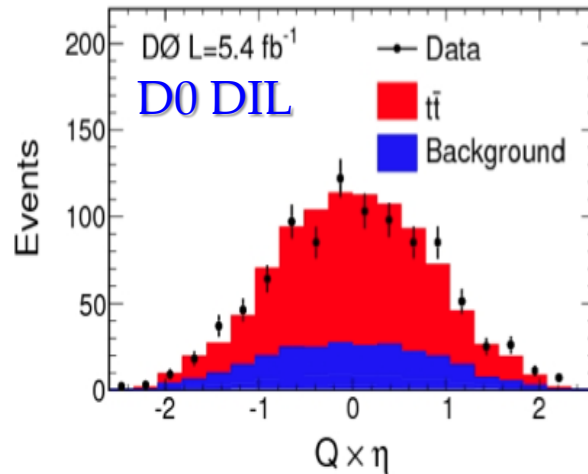
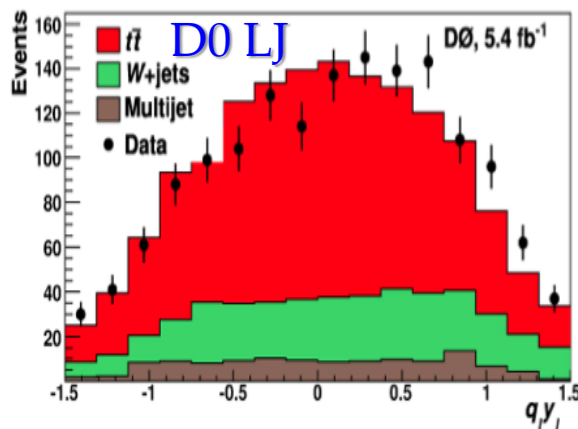


- ✓ The generator-level distributions of qy_ℓ are shown in the left plot
- ✓ Leptonic A_{FB} kinematically correlated with top A_{FB} and manifestation of A_{FB} in the lepton from polarized tops.

$$A_{FB}^l = \frac{N_l(Q \cdot \eta > 0) - N_l(Q \cdot \eta < 0)}{N_l(Q \cdot \eta > 0) + N_l(Q \cdot \eta < 0)}$$

- ✓ Reconstructed lepton η is systematically unencumbered

Lepton Asymmetry at Tevatron



✓ D0 LJ - 5.4 fb^{-1} [PRD 84, 112005 (2011)]

- Observed $A_{\text{FB}} = 14.2 \pm 3.8\%$, **Parton-level $A_{\text{FB}} = 15.2 \pm 4.0\%$** (SM Prediction: $4.7 \pm 0.1\%$)

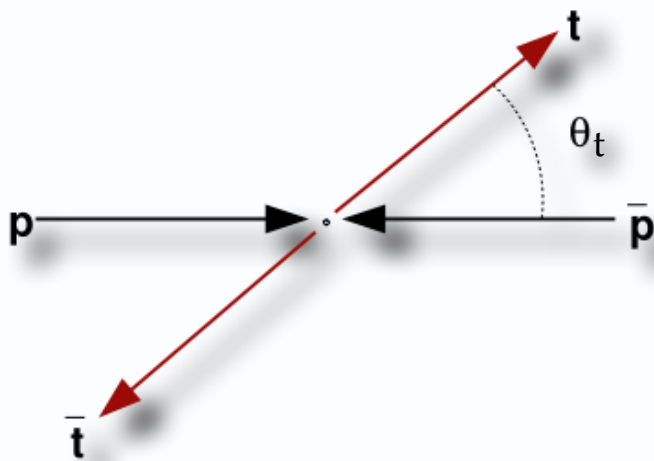
✓ D0 DIL - 5.4 fb^{-1} [PRD 87, 011103(R) (2012)]

- Observed $A_{\text{FB}} = 3.1 \pm 4.4\%$, **Parton-level $A_{\text{FB}} = 5.8 \pm 5.3\%$** (SM Prediction: $4.7 \pm 0.1\%$)

✓ CDF LJ - 9.4 fb^{-1} [CDF Public Note 10975]

- Observed $A_{\text{FB}} = 7.0 \pm 2.2\%$, **Parton-level $A_{\text{FB}} = 9.4^{+3.2}_{-2.9}\%$** (SM Prediction: $3.6 \pm 0.2\%$)

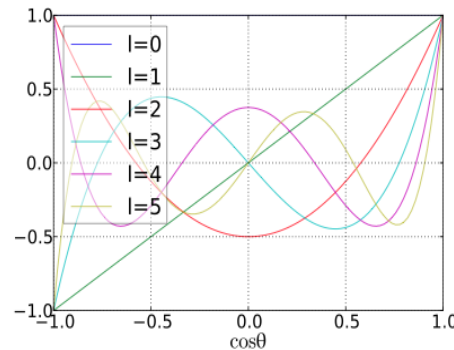
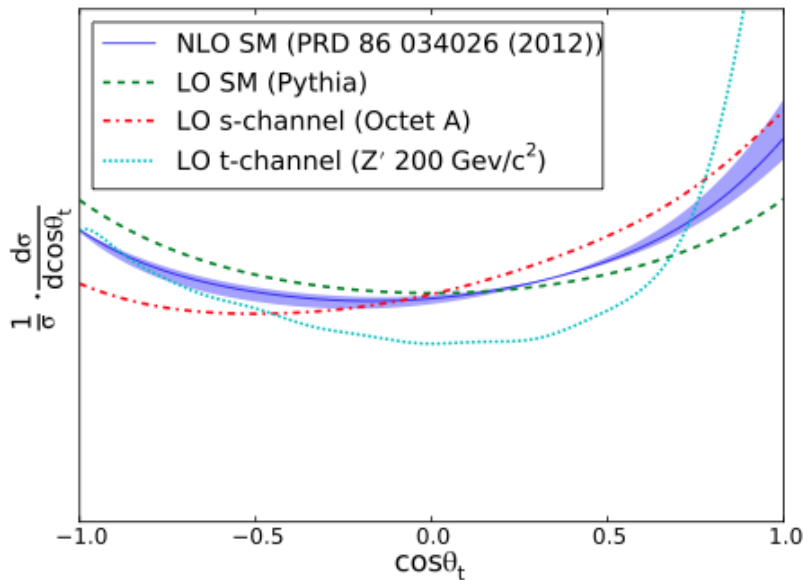
Top A_{FB} in Angular $t\bar{t}$ cross section



- ✓ Top AFB in the differential cross section, $d\sigma/d\cos\theta_t$ where θ_t is the angle between the top quark momentum and the incoming proton momentum as measured in the $t\bar{t}$ center-of-mass-frame
- ✓ Characterize the shape of $d\sigma/d\cos\theta_t$ by expanding in the Legendre polynomials

$$\frac{d\sigma}{d\cos\theta_t} = \sum_{\ell} a_{\ell} P_{\ell}(\cos\theta_t)$$

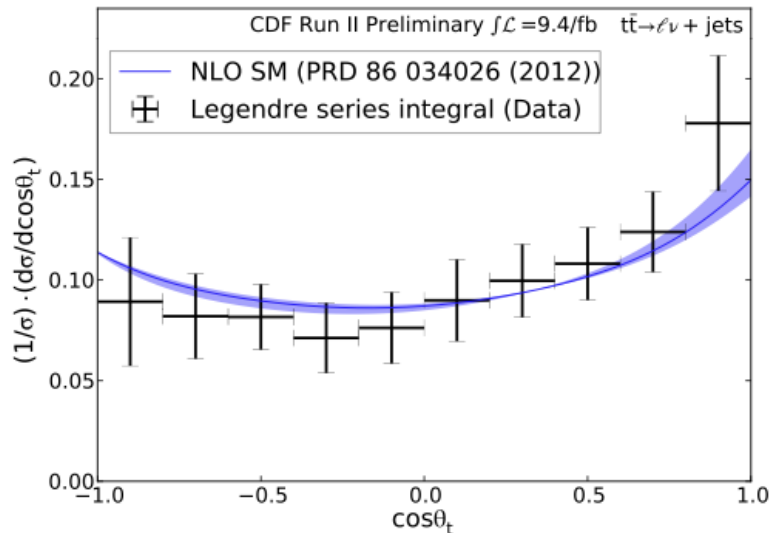
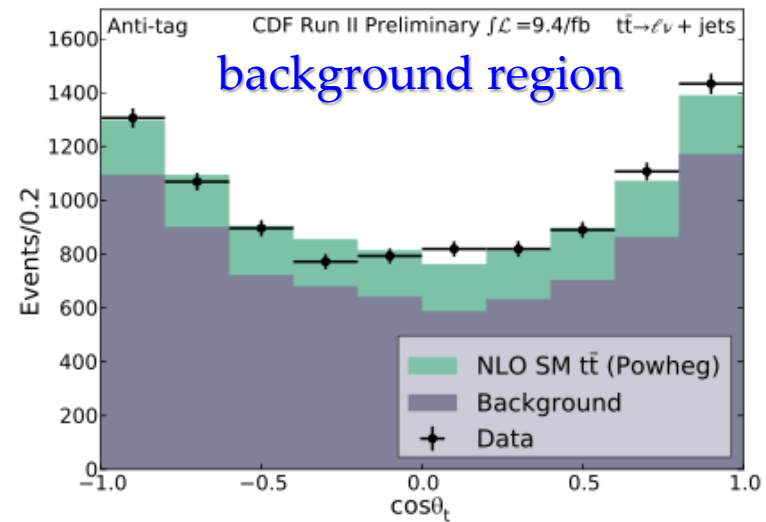
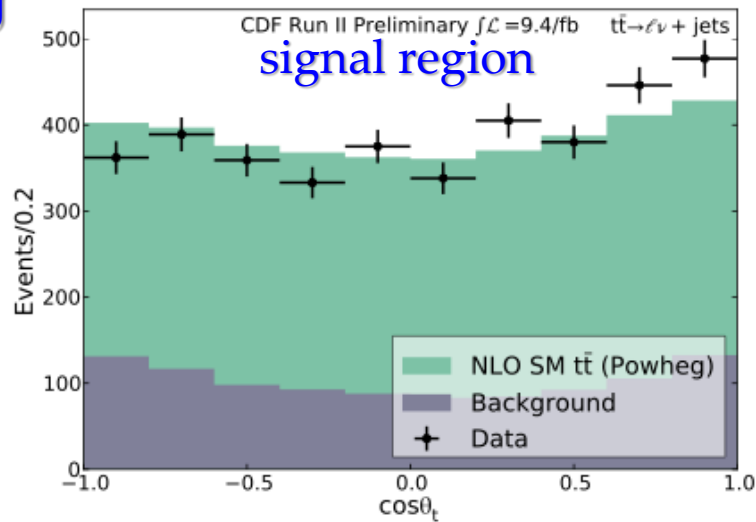
- ✓ where P_{ℓ} is the Legendre polynomial of degree ℓ , and a_{ℓ} is the Legendre moment of degree ℓ



| ℓ | $P_{\ell}(x)$ |
|--------|------------------------------------|
| 0 | 1 |
| 1 | x |
| 2 | $\frac{1}{2}(3x^2 - 1)$ |
| 3 | $\frac{1}{2}(5x^3 - 3x)$ |
| 4 | $\frac{1}{8}(35x^4 - 30x^2 + 3)$ |
| 5 | $\frac{1}{8}(63x^5 - 70x^3 + 15x)$ |

Top A_{FB} in Angular $t\bar{t}$ cross section

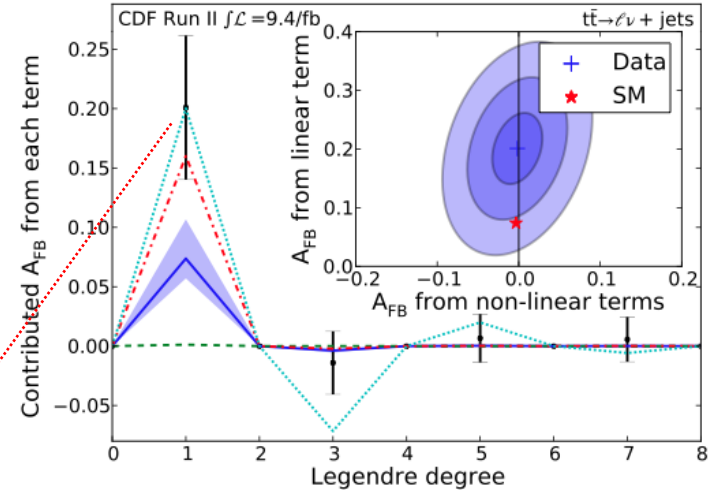
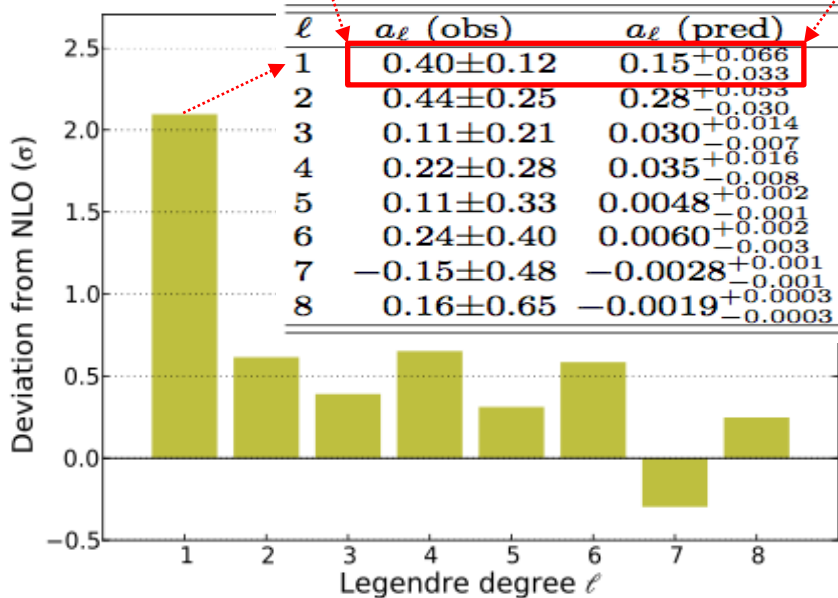
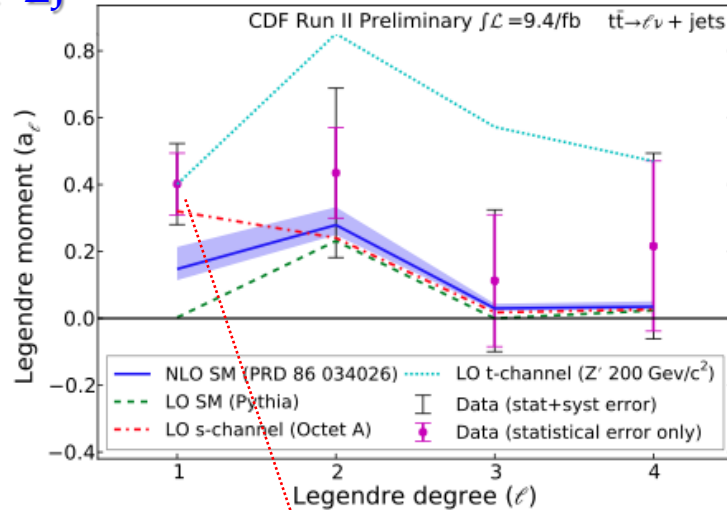
CDF LJ



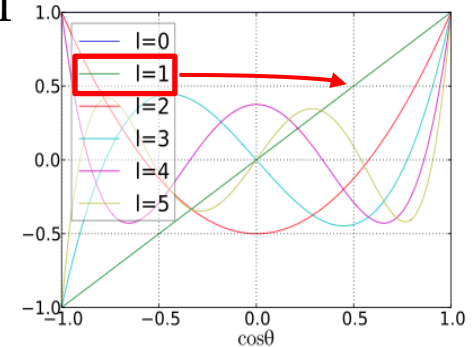
- ✓ The signal+background model generally performs well, except for the presence of a A_{FB} in the data that is not modeled by our signal MC
- ✓ Integrating the Legendre series over finite-width bins gives the fraction of cross section in each bin of $\cos\theta_t$. Uncertainties are highly correlated and are dominated by the large uncertainties on the higher-order moments

Top A_{FB} in Angular $t\bar{t}$ cross section

CDF LJ



- ✓ The given Z' model is not consistent with data
- ✓ Legendre moments consistent with prediction except for the first moment 2.1σ from NLO SM
- ✓ The excess is linear term in differential cross section



Top A_C @ LHC

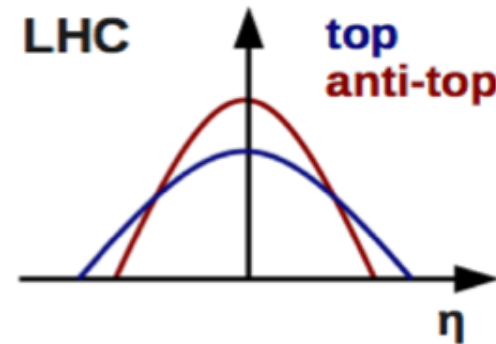
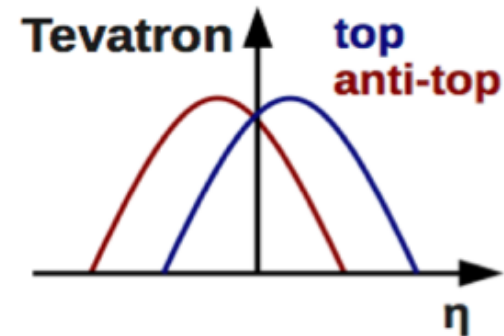
- ✓ At LHC, the top quark pairs are produced through gg fusion (~80%) and qq hard collisions (~20%)
 - qg partonic processes is almost negligible
- ✓ Tiny NLO QCD effect: $A_C = 1.15 \pm 0.06\%$ *
 - Challenging to measure. Only ~10% A_C expected from A_{FB} at Tevatron.
- ✓ Symmetry of the incoming beams, an asymmetry based on the Δy variable would vanish. $\Delta|y|$ or $\Delta|\eta|$ is chosen

$$\Delta|y| = |y_t| - |y_{\bar{t}}| \quad \Delta|\eta| = |\eta_{t+}| - |\eta_{t-}|$$

- ✓ The charge asymmetry is defined by

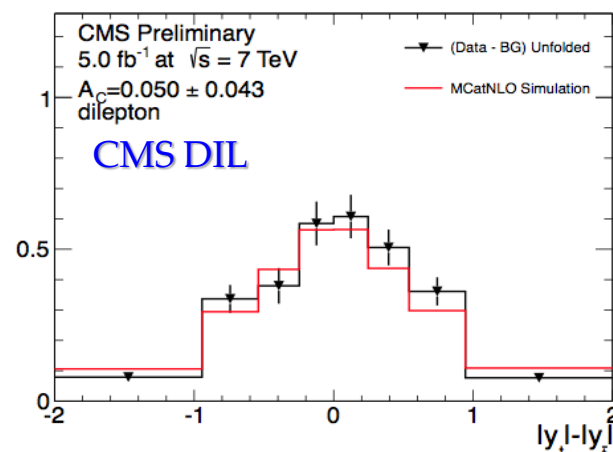
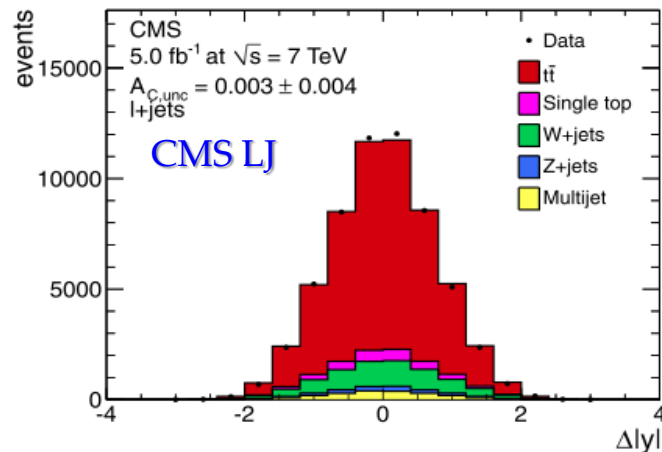
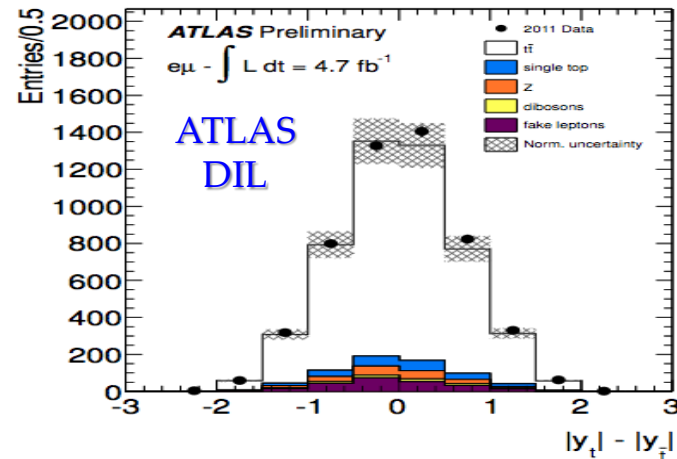
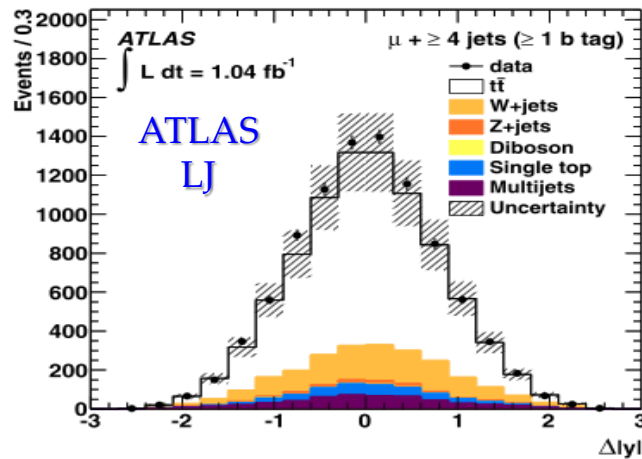
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \quad \text{for lepton+jets channel}$$

$$A_C^{\eta} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)} \quad \text{for dilepton channel}$$



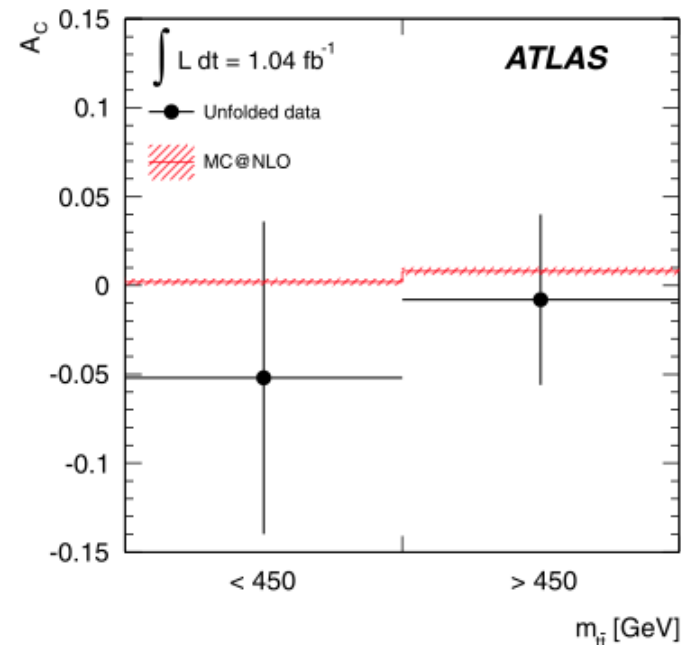
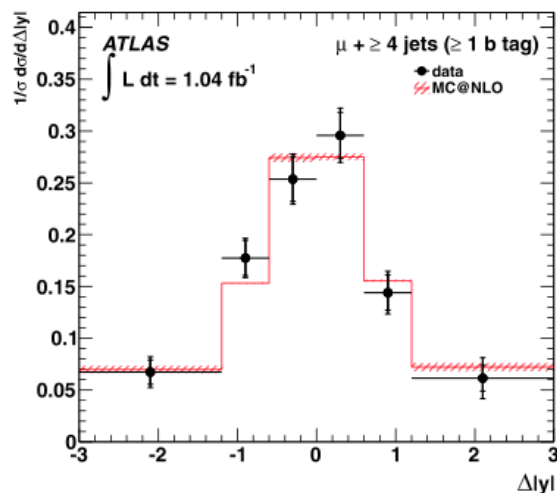
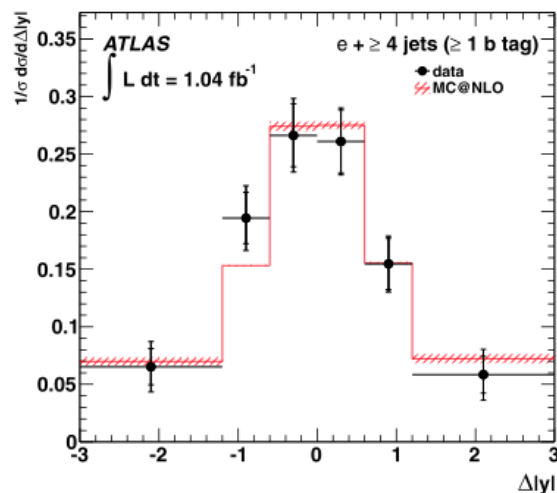
* J. H. Kühn and G. Rodrigo, JHEP 1201 (2012) 063

Top $\Delta|y|$ asymmetry at LHC



✓ No significant deviation from SM prediction for ATLAS and CMS (LJ and DIL channel)

ATLAS lepton+jets results



Asymmetry

Reconstructed

Detector and acceptance unfolded

A_C (electron)

$-0.034 \pm 0.019 \text{ (stat.)} \pm 0.010 \text{ (syst.)}$

$-0.047 \pm 0.045 \text{ (stat.)} \pm 0.028 \text{ (syst.)}$

A_C (muon)

$-0.010 \pm 0.015 \text{ (stat.)} \pm 0.008 \text{ (syst.)}$

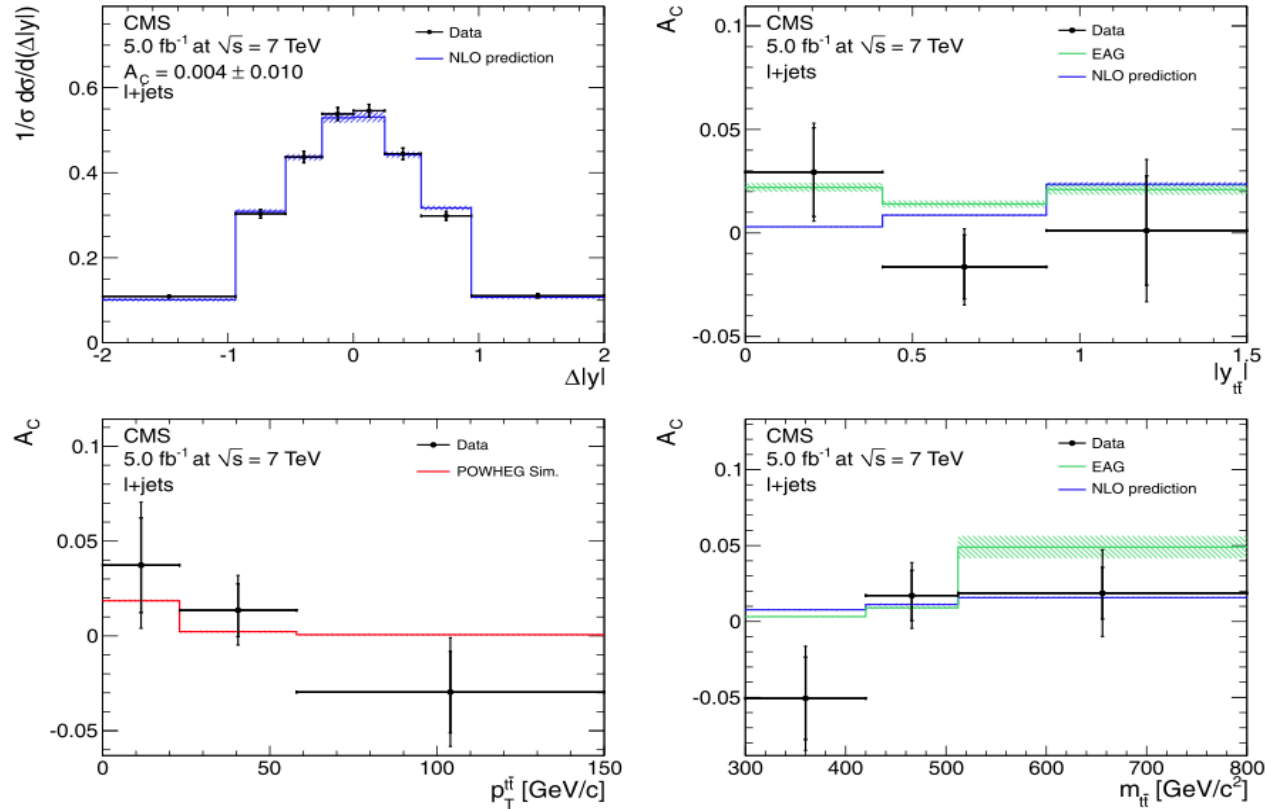
$-0.002 \pm 0.036 \text{ (stat.)} \pm 0.024 \text{ (syst.)}$

Combined

$-0.019 \pm 0.028 \text{ (stat.)} \pm 0.024 \text{ (syst.)}$

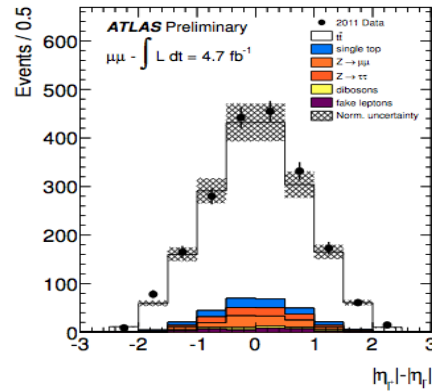
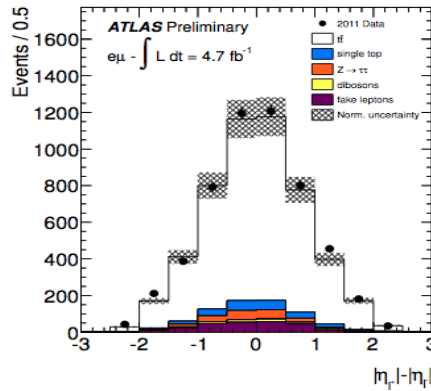
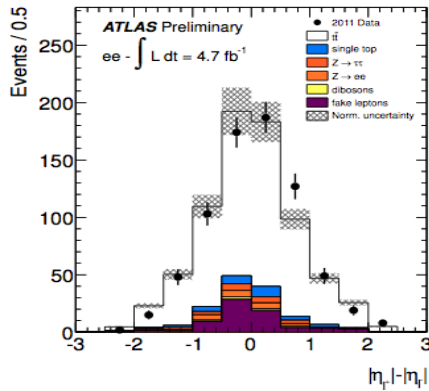
✓ No sign of asymmetry as a function of $M_{t\bar{t}}$

CMS lepton+jets results



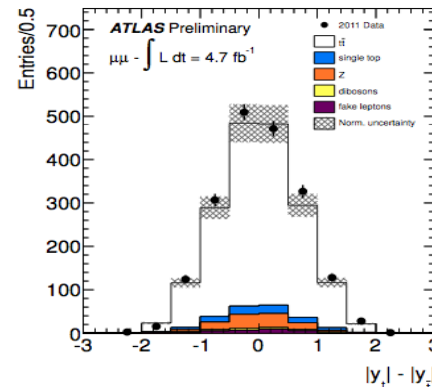
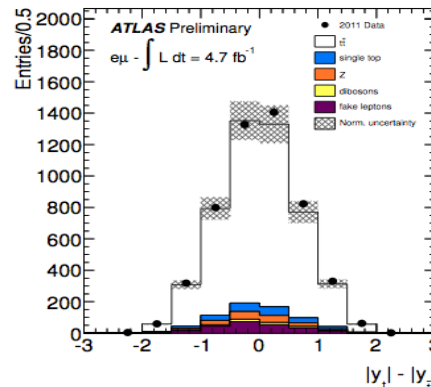
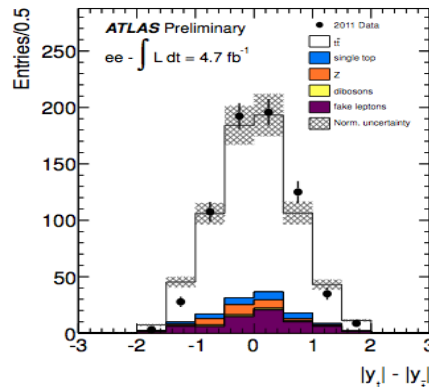
- ✓ Measured $A_C = 0.004 \pm 0.010_{(stat)} \pm 0.011_{(syst)}$
- ✓ Mass dependence : A_C increases as a function of $M_{t\bar{t}}$
- ✓ Rapidity dependence : No sign of A_C increase as a function of $|y_{t\bar{t}}|$
- ✓ A_C depends on p_T of the $t\bar{t}$ system

ATLAS dilepton results



Lepton charge asymmetry

$$A_C^{\ell\ell} = 0.023 \pm 0.012 \text{ (stat.)} \pm 0.008 \text{ (syst.)} \quad \text{SM Prediction: } A_C^{\ell\ell} = 0.004 \pm 0.001$$

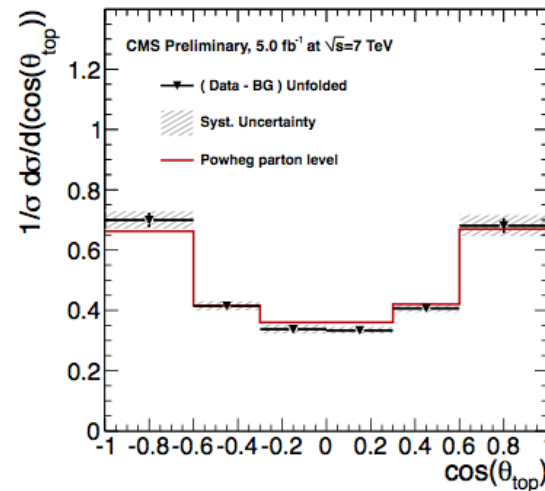
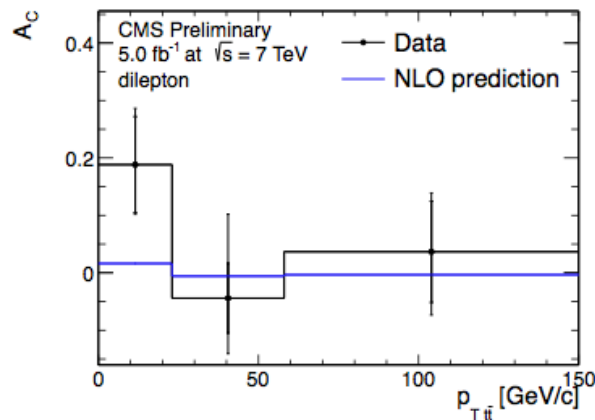
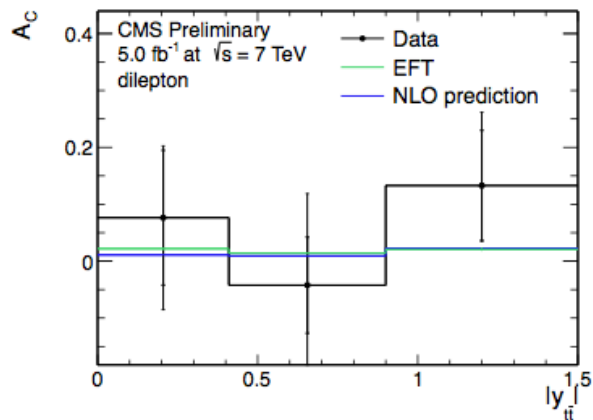
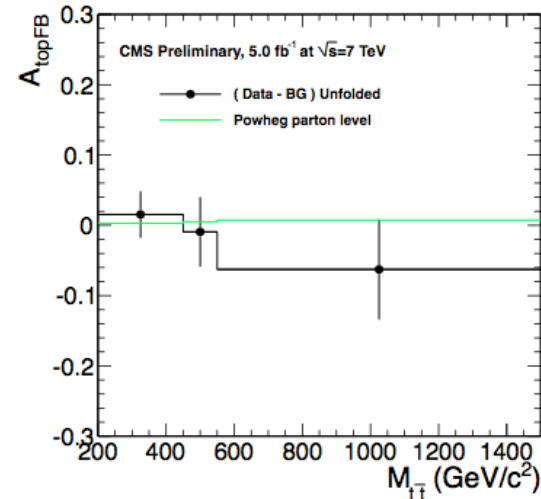
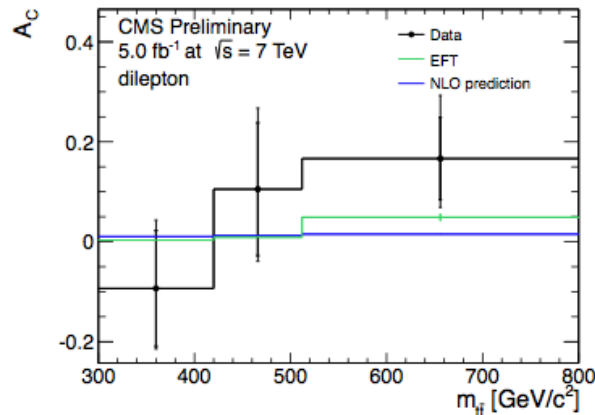
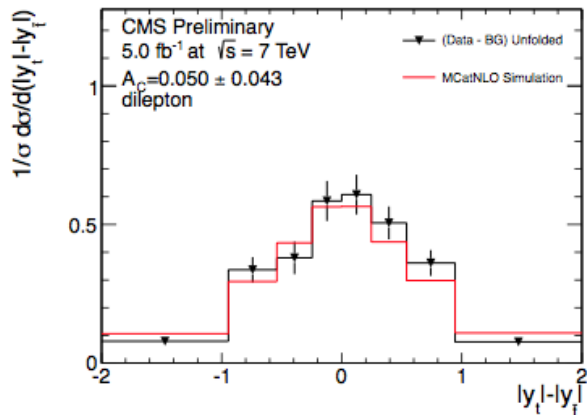


Top-quark charge asymmetry

$$A_C^{t\bar{t}} = 0.057 \pm 0.024 \text{ (stat.)} \pm 0.015 \text{ (syst.)} \quad \text{SM Prediction: } A_C^{t\bar{t}} = 0.006 \pm 0.002$$

✓ Consistent with SM for all dilepton flavor in the uncertainty.

CMS dilepton results



$$A_C^l = 0.010 \pm 0.015_{(stat)} \pm 0.006_{(syst)}$$

$$A_C = 0.050 \pm 0.043_{(stat)} \pm^{0.010}_{0.039(syst)}$$

Conclusion

✓ Top A_{FB} still there at Tevatron

- Many various experimental checks are done by CDF and D0
- Inconsistent with SM calculation
 - The Top asymmetry grows as a function of $t\bar{t}$ mass and rapidity
- Found an anomalously large linear term in the moments of the angular differential cross section
 - The A_{FB} is dominated by this linear term
- More data will be analyzed by D0 and CDF DIL channel

✓ LHC does not see A_C but not quite sensitive yet

- Top charge asymmetry in lepton+jets and dilepton channel and the lepton-based asymmetry measurements by ATLAS & CMS
- Both inclusive and differential measurements have been performed
- The issue is hard to be settled directly for a while. But direct searches for $t\bar{t}$ resonances/etc could probably settle this with LHC 8TeV data
 - The "best" surviving NP model is a light axigluon $M \sim 200$ GeV

Backup

Covariance matrices for $A_{\text{FB}}(|\Delta y|)$ and $A_{\text{FB}}(M_{t\bar{t}})$

| Eigenvalue λ | 0.0293 | 0.00734 | 0.000721 | 0.000497 |
|-----------------------------|--------|---------|----------|----------|
| $ \Delta y < 0.5$ | -0.062 | 0.376 | -0.921 | -0.080 |
| $0.5 \leq \Delta y < 1.0$ | 0.033 | 0.838 | 0.300 | 0.455 |
| $1.0 \leq \Delta y < 1.5$ | 0.471 | 0.347 | 0.179 | -0.791 |
| $ \Delta y \geq 1.5$ | 0.880 | -0.191 | -0.171 | 0.401 |

| Eigenvalue λ | 0.0431 | 0.00158 | 0.00441 | 0.0105 |
|---|--------|---------|---------|--------|
| $M_{t\bar{t}} < 450\text{GeV}/c^2$ | -0.019 | -0.753 | 0.641 | -0.151 |
| $450\text{GeV}/c^2 \leq M_{t\bar{t}} < 550\text{GeV}/c^2$ | -0.009 | 0.612 | 0.597 | -0.519 |
| $550\text{GeV}/c^2 \leq M_{t\bar{t}} < 650\text{GeV}/c^2$ | 0.419 | -0.223 | -0.431 | -0.767 |
| $M_{t\bar{t}} \geq 650\text{GeV}/c^2$ | 0.908 | 0.094 | 0.218 | 0.346 |

A_{FB} at Tevatron vs. A_C at LHC

